WET WEATHER MODEL DEVELOPMENT FOR TRACE METAL LOADING IN AN ARID URBANIZED WATERSHED: BALLONA CREEK, CALIFORNIA

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April 30, 2004

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ABSTRACT

Watershed models, such as the Hydrological Simulation Program – Fortran (HSPF), are widely applied to investigate runoff dynamics and associated pollutant loadings, but applications in arid urban watersheds for trace metals are rarely observed. The efficacy of HSPF in arid urban watersheds is questioned since very short time scales (i.e. minutes) are needed to understand the processes associated with these flashflood events in highly impervious areas. In this study, HSPF is developed for simulating concentrations and loads of total suspended solids (TSS), copper, lead, and zinc at one-minute intervals in the Ballona Creek watershed, which comprises an exceptionally urbanized section of Los Angeles, CA. The model was calibrated in small homogeneous land use sites and then validated at an instream site that received cumulative discharges from multiple land uses upstream. Model evaluation focused on the ability to predict storm event mean concentrations (EMCs) and time-concentration series, which measures the changes in TSS and trace metal concentrations during rising, peak and receding storm flows. HSPF was capable of reproducing the observed time-concentration series and corresponded closely to the measured EMCs for TSS, copper, lead, and zinc at each of the land use calibration sites. Similarly, the model reproduced the observed time-concentration series and corresponded closely to the measured EMCs for TSS, copper, lead, and zinc at the instream validation site. The most problematic trace metal to model was zinc, which typically overestimated the measured concentration. For all metals, the correlation between loading and rainfall varied by storm size. All four water quality constituents were significantly highly correlated to rainfall during large storm events (≥ 2.54 mm), but rainfall was a poor predictor of constituent loading during small storm events (< 2.54 mm). This relationship was likely due to poor rainfall characterization during the small storm events.

INTRODUCTION

Watershed models are widely applied to investigate runoff dynamics and associated pollutant loadings. The Hydrological Simulation Program – Fortran (HSPF) (Bicknell *et al.* 2001) is one of the more popular of these models, having been applied to simulate runoff loading from urban (Brun and Band 2000) and agriculture (Donigian *et al.* 1983; Moore *et al.* 1988) watersheds. It is a flexible model that has been used to address a wide variety of management issues (Bicknell *et al.* 1984), including urbanization-related changes in stream flow (Ng and Marsalek 1989) and sediment transport (Chew *et al.* 1991).

Changes in streamflow and sediment transport are not the only alterations of stream water quality that managers often address. Many streams have degraded water quality because of excessive trace metal loadings that may lead to acute and chronic toxicity to aquatic organisms (Boulanger and Nikolaidis 2003). Trace metal loadings may also be incorporated into estuarine sediments (Schiff *et al.* 2002) where watershed discharges may accumulate. For example, trace metal contributions from heavily urbanized watersheds in the southern California region have been identified as the primary toxicants impacting organisms in receiving waters (Bay *et al.* 1998; Schiff *et al.* 2002). Near coastal sediments impacted by urbanized watershed discharges, particularly during wet weather flows, have contributed to sediment contamination by trace metals (Schiff and Bay 2003). Despite the identified impacts, few HSPF applications are found in the literature that address trace metal loadings to streams.

The majority of HSPF applications focus on watersheds with perennially flowing streams, while applications in arid urban watersheds with naturally low, or absent, dry season flow have not been extensively documented (Berris *et al.* 2001; Guay 2002). Arid, urbanized watersheds present unique issues in temporal resolution. Arid watersheds often have no, or very little, flow when it is not raining, then increase orders of magnitude within an hour and typically recede to baseflow in less than a day. These “flash flood” type conditions are exemplified by the arid urban watershed of the Santa

Ana River, where flows increased from <0.001 cms to >1,000 cms during a single 6 hr storm event (Tiefenthaler *et al.* 2001). In contrast, HSPF applications in continuously flowing streams with groundwater or snow melt processes are typically analyzed on daily, and often longer, time scales. In order to capture the dynamic processes of arid urban environments, simulations should be conducted on time scales of minutes. Understanding within storm processes is especially important if the resulting model is to be used for predicting the effectiveness of stormwater controls. This is because most control strategies are necessarily focused on only a portion of a storm event, since the ability to capture the large volumes associated with infrequent, but intense storms may be infeasible.

The goal of this study was to investigate HSPF's applicability to accurately model trace metals and total suspended solids (TSS) in an arid urban watershed. In order to address the needs of arid urban watersheds, the development of HSPF was focused on simulating storm water quality on short (i.e. minute) time scales. Simulating water quality in this study builds upon previous work by Ackerman *et al*. (2001), who investigated the applicability of HSPF to model runoff hydrology at short time scales in arid urban watersheds. The previous work by Ackerman *et al*. (2001) identified that HSPF performed well at simulating storm flows when rainfall coverage and channel geometry were accurately characterized. Channel geometry was typically well-characterized because many of the channels were engineered for flood control. Rainfall characterization was also well-characterized for regionwide storm events (> 2.54 mm), but the accuracy of flow simulations decreased with smaller, more isolated storm events (< 2.54 mm)..

METHODS

Approach

A three-step approach was used to investigate HSPF's applicability to accurately model trace metals and TSS in an arid urban watershed. The first step was to mimic the model development in Ballona Creek for flow and volume described by Ackerman *et al*. (2001). The second step was to calibrate the model for TSS by reproducing time-concentration series at small, homogeneous land use sites. A time-concentration series is 10 to 12 individually analyzed grab samples collected over the course of a storm event to represent the changes in concentration during rising, peak, and tailing flows of the hydrograph. Once TSS was calibrated, three trace metals (copper, lead, and zinc) were calibrated for each land use. Since TSS and each of the trace metals were highly significantly correlated, a potency factor was applied to the TSS to represent each of the trace metal concentrations. Potency factors indicate the "constituent strength relative to the sediment removed from the surface" (Bicknell *et al.* 2001). The third step was to validate the model at a downstream location in the watershed that represented cumulative storm event discharges from a wide variety of land use types. Simulation of time-concentration series at the downstream location was first examined for TSS, and then repeated for each of the three trace metals.

Area description

The Ballona Creek watershed was used for evaluation of HSPF in this study. Ballona Creek is a highly developed watershed comprising a large section of the municipal Los Angeles area; approximately 90% of the watershed is developed urban space. At 338 km^2, Ballona Creek is the largest watershed that drains to Santa Monica Bay, CA.

Ballona Creek is also an arid watershed. The watershed has averaged 20 storms and 34 cm of precipitation per year since 1947 (Ackerman and Weisberg 2003). Historically, portions of the upper watershed received as much as 53 cm annually, mostly due to orographic differences on south facing slopes of the coastal foothills. Seventy percent of the annual rainfall occurs between January and March, with virtually no rain from May through October (Ackerman and Weisberg 2003).

Data sources

HSPF uses rainfall, land use characteristics, and stream geometry to predict flow. Rainfall data for the Ballona Creek watershed were obtained from LACDPW (Los Angeles County Department of Public Works) Gage 10A, Los Angeles International Airport (LAX), and the University of Southern California (USC) (LACDPW 2003; NCDC 2004). Rain data for land use catchments were obtained from nearby gages supported by LACDPW, or by deployment of rain gages at each of the land use sites. All gages measured rainfall in 0.254 mm increments.

Detailed land use data were obtained from the Southern California Association of Governments (Southern California Council of Governments 1993). Land use data were aggregated to 8 categories based on like activities. Minimum land use resolution was 8 m^2. The percent of perviousness for each land use was established following LACDPW methods (DePoto *et al.* 1991) (Table 1).

The Ballona Creek watershed was divided into seven sub-basins (LACDPW 1999) for model application. Streams in the Ballona Creek watershed are concrete-lined trapezoidal or rectangular channels. Stream geometry was defined using as-built drawings (LACDPW 1999).

Continuous flow data from Ballona Creek were obtained from an established gage maintained by the LACDPW (LACDPW 2003). Flow was also measured at each of the land use sites for specific storm events using area-velocity sensors and/or bubblers, each with automated data loggers.

Water quality data to support model calibration at land use sites, and model validation at downstream sites, were collected using a targeted sampling program to develop time-concentration series for TSS and trace metals. A review of the sampling program has been reported by others (Schiff and Sutula 2004). Briefly, land use sites included high density residential, low density residential, commercial, agriculture, industrial, and open space (Table 1). The single land use catchments ranged from 0.02 to 9.49 km^2; not all of them were located specifically in the Ballona Creek watershed (Figure 1). Instead, land use catchments were selected to be representative of all land uses within this category for the Los Angeles region. Approximately 10 samples were collected per storm event to characterize changes in water quality during the different phases of the storm based on sampling efficiencies described by Leecaster *et al.* (2002). Water quality samples for model validation were collected along the mainstem of Ballona Creek. This site, located at the furthest site downstream where an existing flow gage was operated, captured 74% of the entire watershed (Figure 1).

The water quality sampling program was designed to capture a range of storms from each site, incorporating storm size and antecedent dry days (Table 2). In total, 19 site-events were sampled from six land uses (agriculture, commercial, high density residential, industrial, low density residential, and open). Another four were sampled from the Ballona Creek validation site. Rainfall quantity ranged from 1.27 mm to 15.2 mm per event. Antecedent rainfall likewise varied, ranging from 3 to 31 days.

Assumptions

In any modeling application that attempts to mimic the environment, a series of assumptions must be made. Many of the assumptions are inherent in HSPF and can be found in Bicknell *et al.* (2001). In addition there were five primary model assumptions used in this study:

1) The sampled land use catchments were representative of the land uses throughout the watershed.
2) The sediment washed off pervious areas uniformly regardless of the land use type. Sediment washed off impervious areas heterogeneously and the wash off was dependent on land use type.

3) Sediment and trace metal washoff was consistent throughout the year.
4) The sediment washoff was partitioned as 5% sand, 55% silt and 40% clay.
5) Trace metals were linearly related with TSS and completely particulate-bound during washoff.

Perhaps the most explicit of these assumptions is that trace metals were linearly related to TSS. This assumption stems from the potency factor used in modeling trace metals. This assumption appears warranted based on empirical results from stormwater sampling programs from the 12 largest rivers and creeks in southern California including Ballona Creek (Cross *et al.* 1992). For example, copper, lead, and zinc were linearly related to suspended sediments in Ballona Creek and the adjacent Los Angeles River during 1980-87 (Figure 2). Even after updating the empirical data set with samples from 2001-03, the assumption of linearity was true regardless of trace metal.

The model calls for additional non-storm user inputs such as baseflow and groundwater characteristics. We assumed a constant baseflow of 0.085 cms (3 cfs) that was evenly distributed to all Ballona Creek sub-basins. This baseflow is comprised entirely of non-point source anthropogenic inputs. This assumption was extrapolated from average daily flow measurements from June to August from 1977 to 1999 of 0.34 cms (12 cfs) at the Sawtelle flow gage. The water quality concentration assigned to the non-point sources was derived from long-term monthly monitoring conducted by the City of Los Angeles and two summer low flow surveys (City of Los Angeles, unpublished data).

Rainfall that infiltrates into the ground has several flow pathways in HSPF. One of the pathways is flow into the stream via interflow and active groundwater flow. These flows require constituent concentrations to be assigned to them a priori since HSPF does not include a groundwater quality module. The interflow and active groundwater flows were assigned the same constituent concentrations as the baseflow.

Model calibration

The model calibration was accomplished in a three-step process. First, the model was run and output on a 1-minute time step with metals accumulation and removal occurring every interval. Second, the modeled hydrology of each land use catchment was compared with the observed flow to ensure that the measured rainfall was representative of the rain on the catchment. Specifically, we examined timing of flow and total storm volume by comparing simulated events to measured events. Third, each catchment was calibrated for TSS concentration. Specifically, we compared TSS levels from the time-concentration series to the simulated storm event by selecting the model TSS output at the time of sampling. To summarize these comparisons, event mean concentrations (EMCs) and flow-weighted 95% confidence intervals were calculated for both the time-concentration and corresponding simulated storm events at each of the land uses. The process of comparison to time-concentration series and EMCs was repeated for copper, lead, and zinc. All calibrated model parameters are in Appendix A.

Model validation

The model validation was accomplished in a three-step process similar to calibration: hydrology, TSS, and finally trace metals. Time-concentration series and EMCs were compared over four storm events captured in the Ballona watershed. The main difference was that the validation site was situated near the base of the watershed and represented the cumulative loading of many land uses upstream. No model parameters were altered after calibration, so this comparison represented an independent validation of hydrology and pollutant transport.

Model evaluation

Once validated, the model was run to assess storm specific loading of TSS, copper, lead, and zinc from the Ballona Creek watershed. The model application focused on storm events between 1990 and 1999. This time period was chosen because it is a representative decade that includes a range of storm sizes including dry years, median years, and wet (El Nino) years. Storm events were defined as the time from the onset of a rain event until either the next day of rain or until the average daily flow was 0.57 cms (20 cfs). A total of 226 storm events occurred during the decadal model run ranging from 0.04 to 265 mm of rainfall. Storms were divided into large (≥ 2.54 mm) and small (< 2.54 mm) events to assess the relationship of rainfall and water quality loading among storm size.

RESULTS AND DISCUSSION

Hydrology Calibration and Validation

HSPF was capable of reproducing hydrographs at land use calibration sites and at the instream validation site. An example hydrograph from a storm on February 19, 2001 indicates that timing of rising, peak and receding flows corresponded nearly identically (Figure 3). This model accuracy is evident in comparison of storm volumes at the Ballona Creek instream validation site. The difference between measured and modeled volume was between 25% and -29%, averaging 1% different among all storm combined (Figure 4). These results are consistent with Ackerman *et al.* (2001) who was able to simulate annual runoff volumes with less than 5% error.

Water Quality Calibration

HSPF was capable of reproducing time-concentration series for TSS copper, lead, and zinc at land use calibration sites (Figure 5). In the example time-concentration series from the high density residential land use on February 19, 2001, the timing of peak concentrations coincided identically regardless of constituent. The magnitude of concentrations in receding flows was closely mimicked for TSS and lead. However, model calibrations underestimated the magnitude of concentrations in receding flows by approximately 50% for copper and lead.

The modeled EMCs corresponded closely to measured EMCs for all of the land uses regardless of constituent (Figure 6). The average difference between measured and modeled EMCs ranged from 10% (TSS and zinc) to 18% (copper) for all land use storm events. Only one (copper) or two (TSS and Zinc) of the 15 storm events had statistically different modeled EMCs compared to measured EMCs. The most problematic constituent was lead, which differed by 78% on average among the 15 different land use storm events. In this case, there were five storm events that had statistically different modeled EMCs compared to measured EMCs. The percent difference of modeled to measured EMCs dropped to less than 6% after removal of these statistically different EMCs.

The same storm events tended to be problematic for each of the trace metals. For example, the storm event at the commercial land use site on February 17, 2002 had dissimilar EMCs for both copper and lead. Likewise, the storm event at the agricultural land use (February 19, 2001) and at the low density residential land use (March 4, 2001) had dissimilar EMCs for TSS, lead and zinc. After examining the hydrographs and time-concentration series for these specific events (data not shown), it was clear that the differences in concentration could be attributed to, poor rainfall characterization that led to inaccurate simulations. In all three problematic storm events, the sampling locations did not have on on-site rain gages. Instead, rainfall was extrapolated from the LACDPW rain gage network, which was located up to 16 km away.

Water Quality Validation

Instream model validation showed good correlation between measured and modeled concentrations regardless of constituent. In the example storm from May 2-3, 2003, time-concentration series were reproduced including the timing of peak concentrations and the magnitude of concentrations in rising, peak, and receding flows (Figure 7). Especially notable was the models' ability to simulate the complex double peak, which occurred as the result of delayed rainfall further up the watershed.

The modeled EMCs corresponded closely to measured EMCs for most of the validation storms (Figure 8). The average difference between measured and modeled instream EMCs for Ballona Creek was 9% (TSS), 18% (copper), 34%(lead), and 48% (zinc). None of the modeled instream EMCs were statistically different from the measured instream EMCs for TSS or copper. One (lead) to two (zinc) of the four validation storm events had significantly different modeled versus measured instream EMCs for lead and copper, respectively. Interestingly, the problematic storm event was similar for the two metals (November 24, 2001).

Comparison of Rainfall and Loading

The modeled correlation between water quality loading and rainfall varied by storm size (Figures 9 and 10) for the decadal simulation. All four water quality constituents were significantly highly correlated to rainfall during large storm events (>2.54 mm). In contrast, rainfall was a poor predictor of constituent loading during small storm events (<2.54 mm). This is likely due to poor rainfall characterization during small events. Ackerman and Weisberg (2003) indicated that storms less than 2.54 mm tended to be isolated storm events for which the current rain gage network does not characterize them well. In contrast, storms greater than 2.54 mm tend to be more regional, allowing for improved precipitation estimates from the existing rain gage network. Since storms less than 2.54 mm accounted for only 35% of the storm events over the ten year simulation period, 1% of the total storm volume and less than 0.6% of the total load, predicted loadings during the ten year simulation are likely a reasonable estimate of the overall actual loadings to Ballona Creek.

ACKNOWLEDGEMENTS

The authors are grateful to the City of Los Angeles for providing funding for this modeling effort. We are also indebted to the members of the steering committee for this project: the City of Los Angeles, the Los Angeles Regional Water Quality Control Board, the Los Angeles County Department of Public Works, U.S. Environmental Protection Agency, and Santa Monica Bay Keeper. Much of this work would not have been possible without the extensive stormwater sampling program that has been funded by the Los Angeles County Department of Public Works, Western States Petroleum Association, City of L.A. Bureau of Sanitation, City of LA Department of Water and Power, L.A. County Sanitation District, City of Carson, and L.A. Contaminated Sediments Task Force.

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Figure 1. Site map of the Ballona Creek modeled sub-basins and land use calibration sites (indicated by circles).

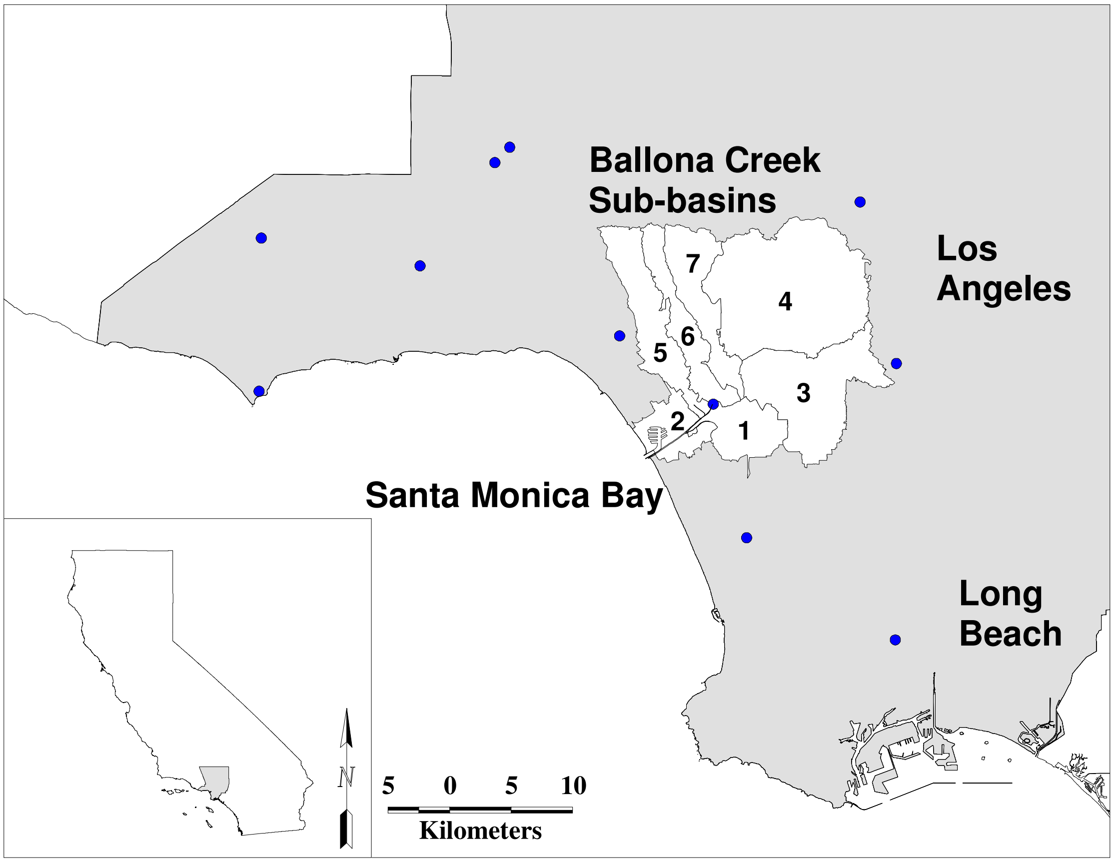

Figure 2. Relationship between measured TSS concentrations and trace metals in Ballona Creek and the Los Angeles River.

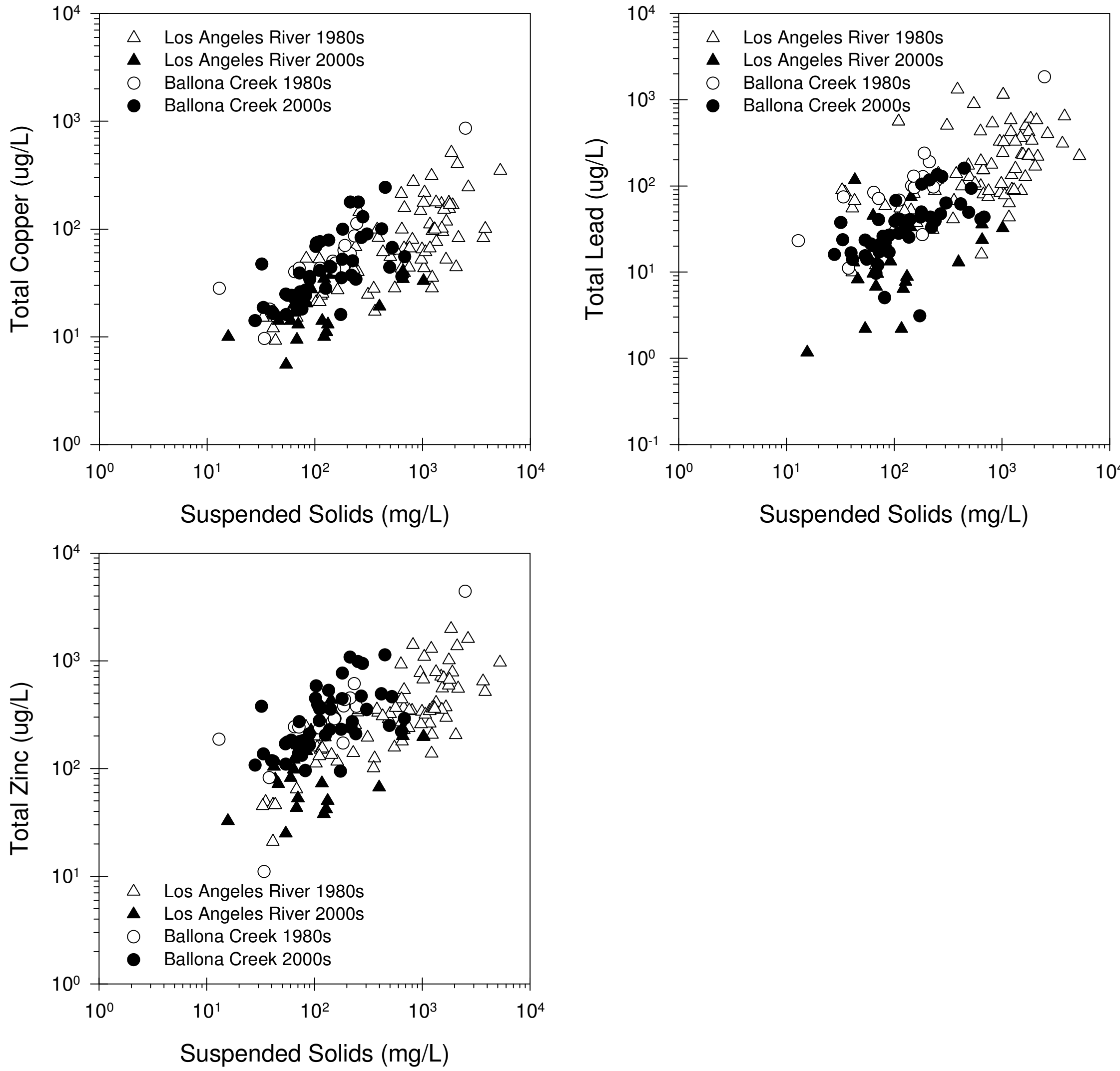

Figure 3. A comparison of the measured and modeled hydrographs from the monitored storm on Feb 19, 2001 for the high density residential site (A) and Ballona Creek (B).

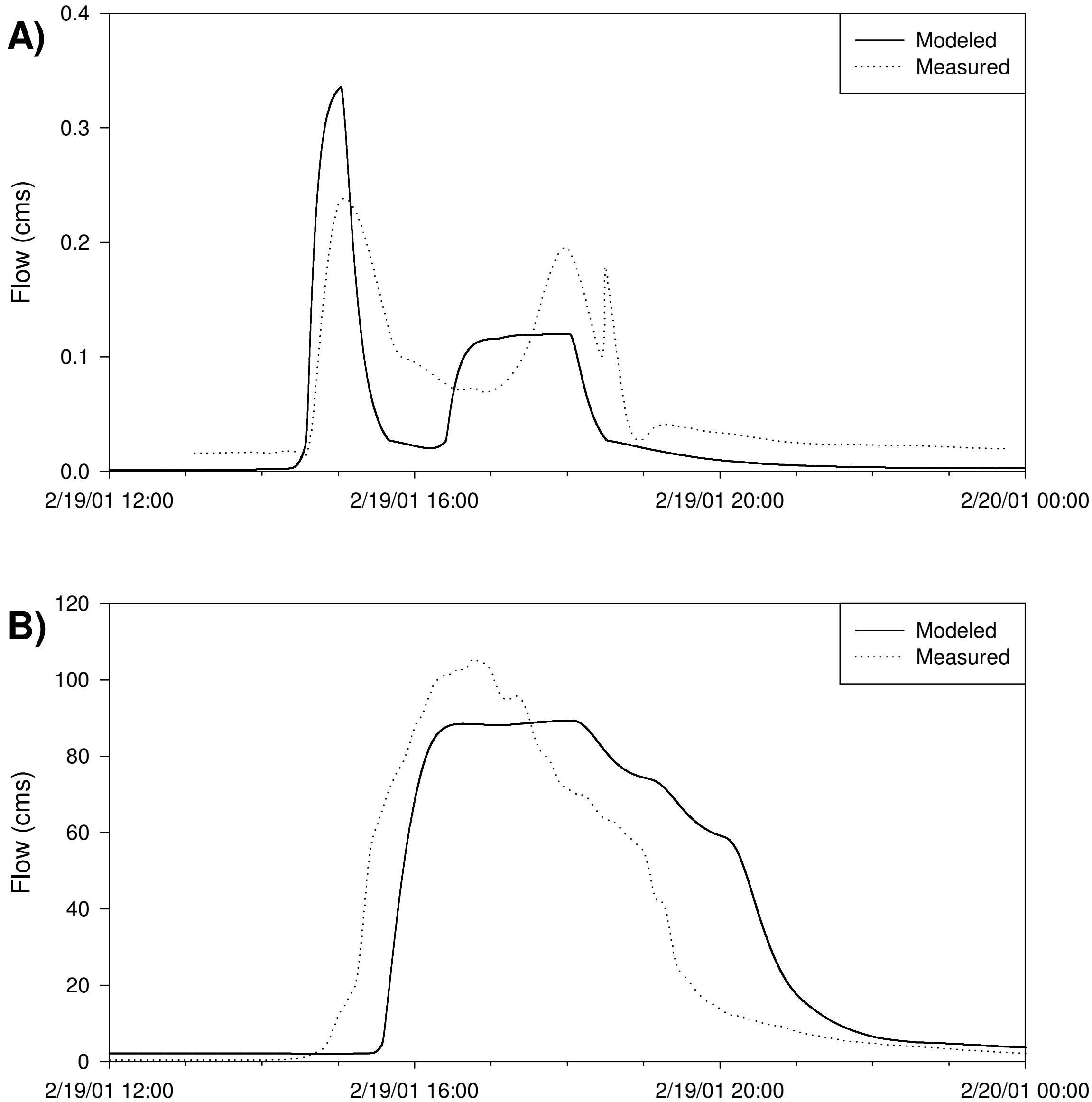

Figure 4. Comparison of measured and modeled storm volumes for Ballona Creek.

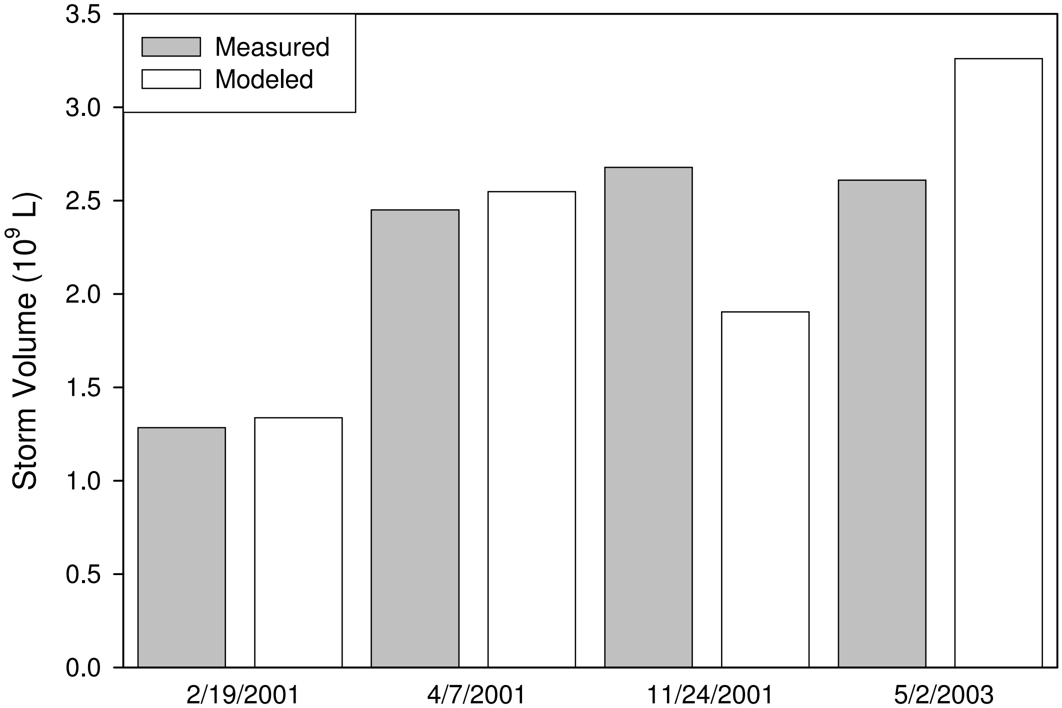

Figure 5. Measured and modeled time-concentration series for TSS (A), copper (B), lead (C), and zinc (D) for the high density residential site during the Feb 19, 2001 sampling.

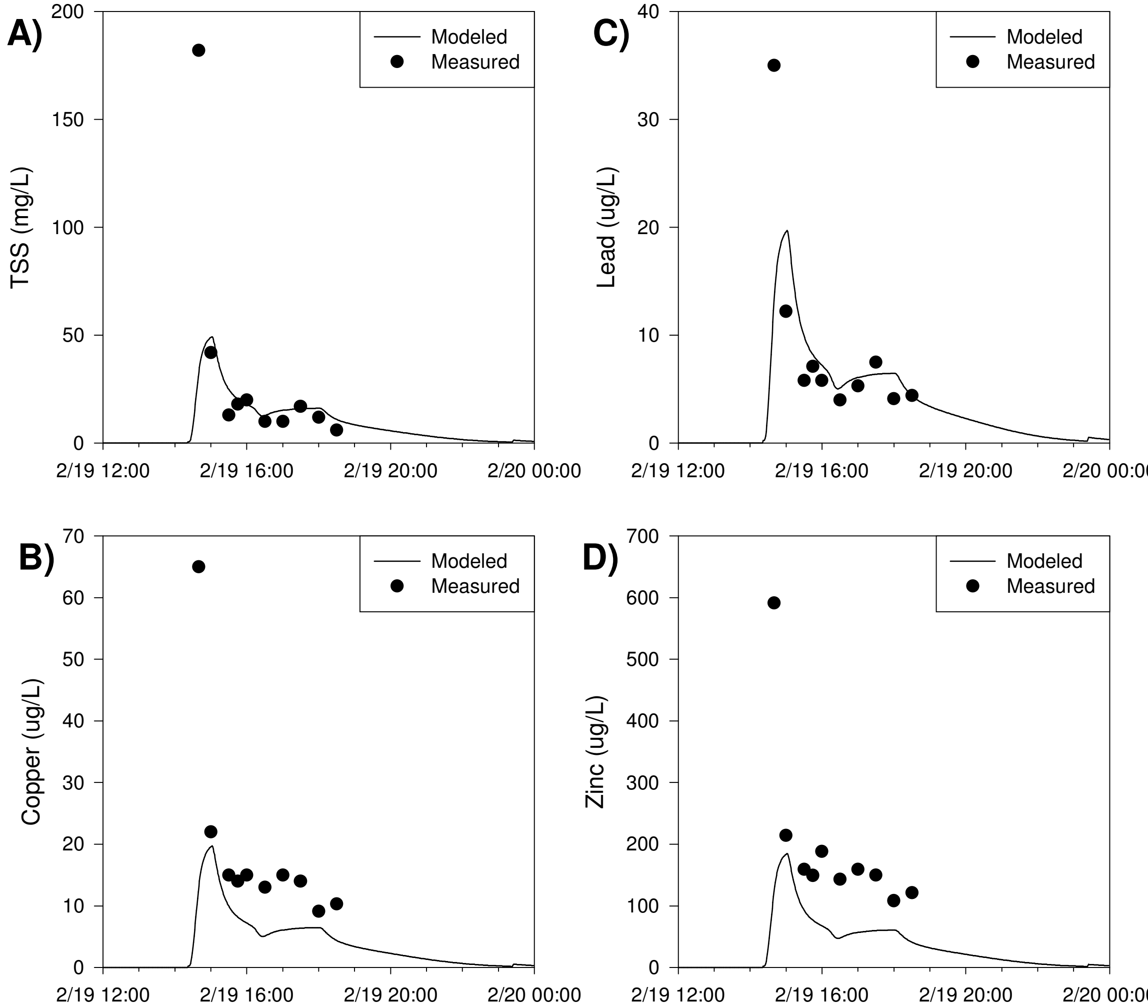

Figure 6. Comparison of event mean concentrations (± 95th percent confidence interval) for measured and modeled site-events by land use catchment. Numbers after the land use designations indicate different sites, letters indicate different storms.

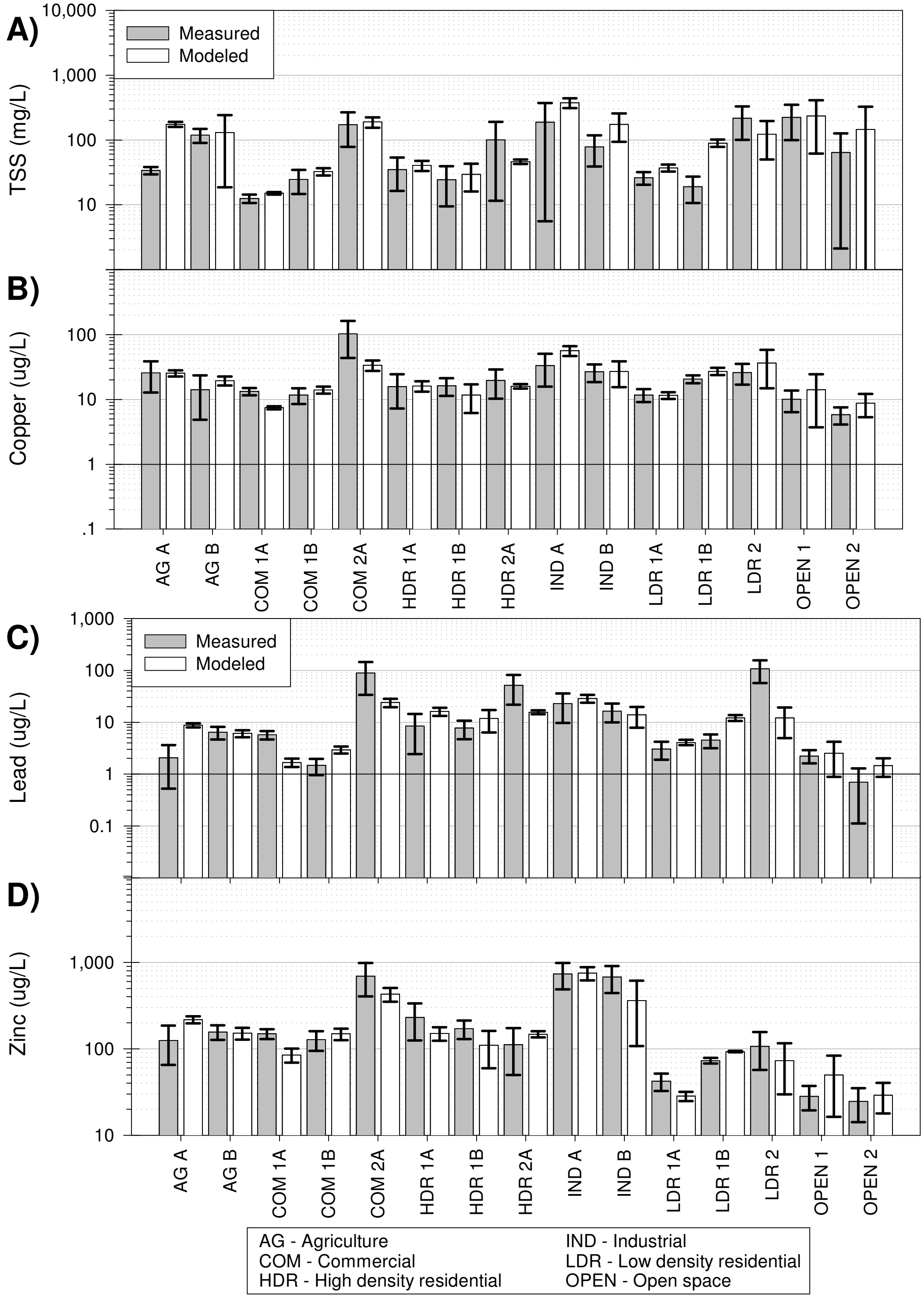

Figure 7. Measured and modeled time-concentration series for TSS (A), copper (B), lead (C), and zinc (D) for Ballona Creek during the May 2, 2003 sampling.

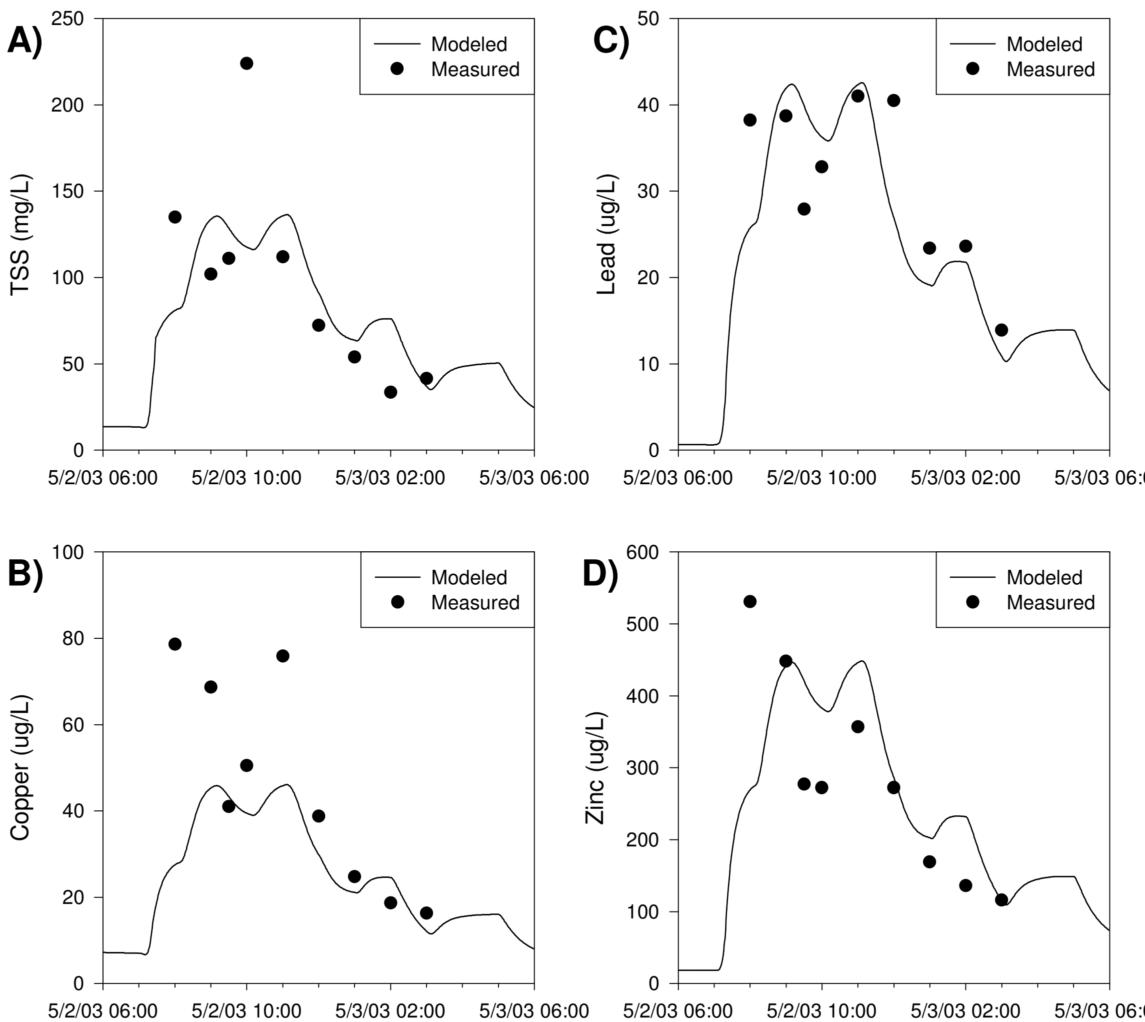

Figure 8. Comparison of event mean concentrations (+/- 95th percent confidence interval) for measured and modeled for different Ballona Creek storms.

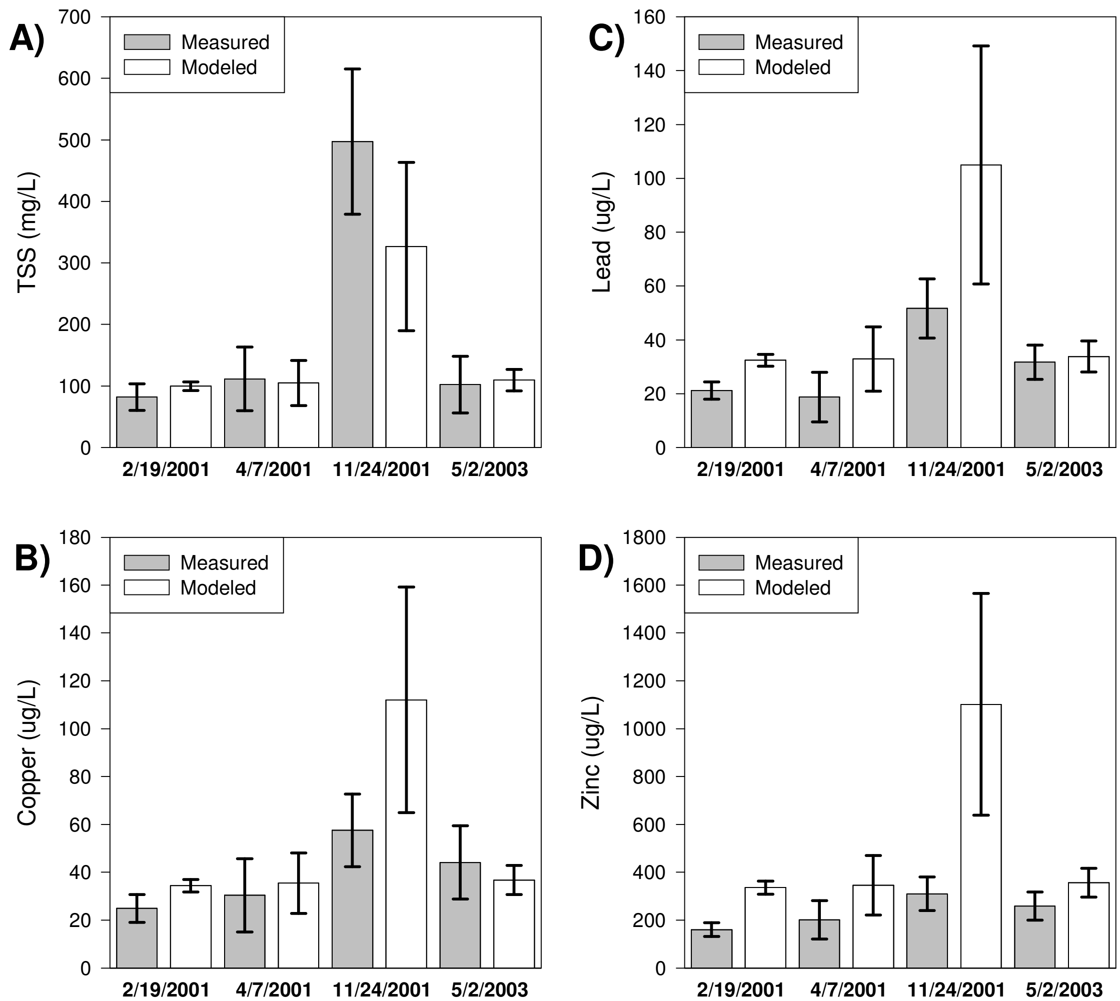

Figure 9. Stormwater loads for TSS (A), copper (B), lead (C), and zinc (D) by area-weighted storm rain volume. Individual storms are represented on the x-axis as categorical data by area-weighted rainfall.

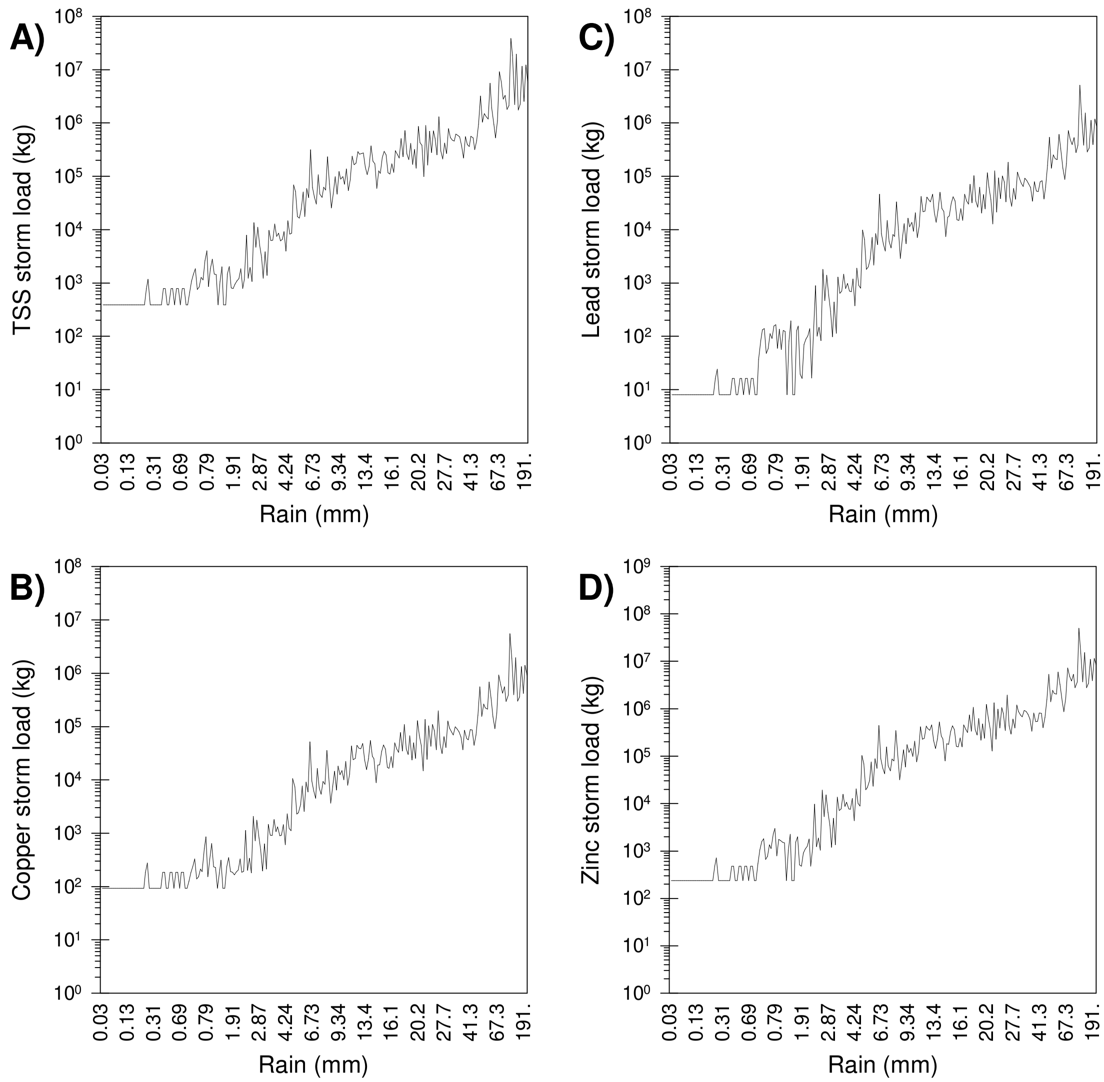

Figure 10. Area-weighted rain versus modeled load of TSS (A), copper (B), lead (C), and zinc (C) for Ballona Creek. The line is the best-fit regression of storms greater than or equal to 2.54 mm.

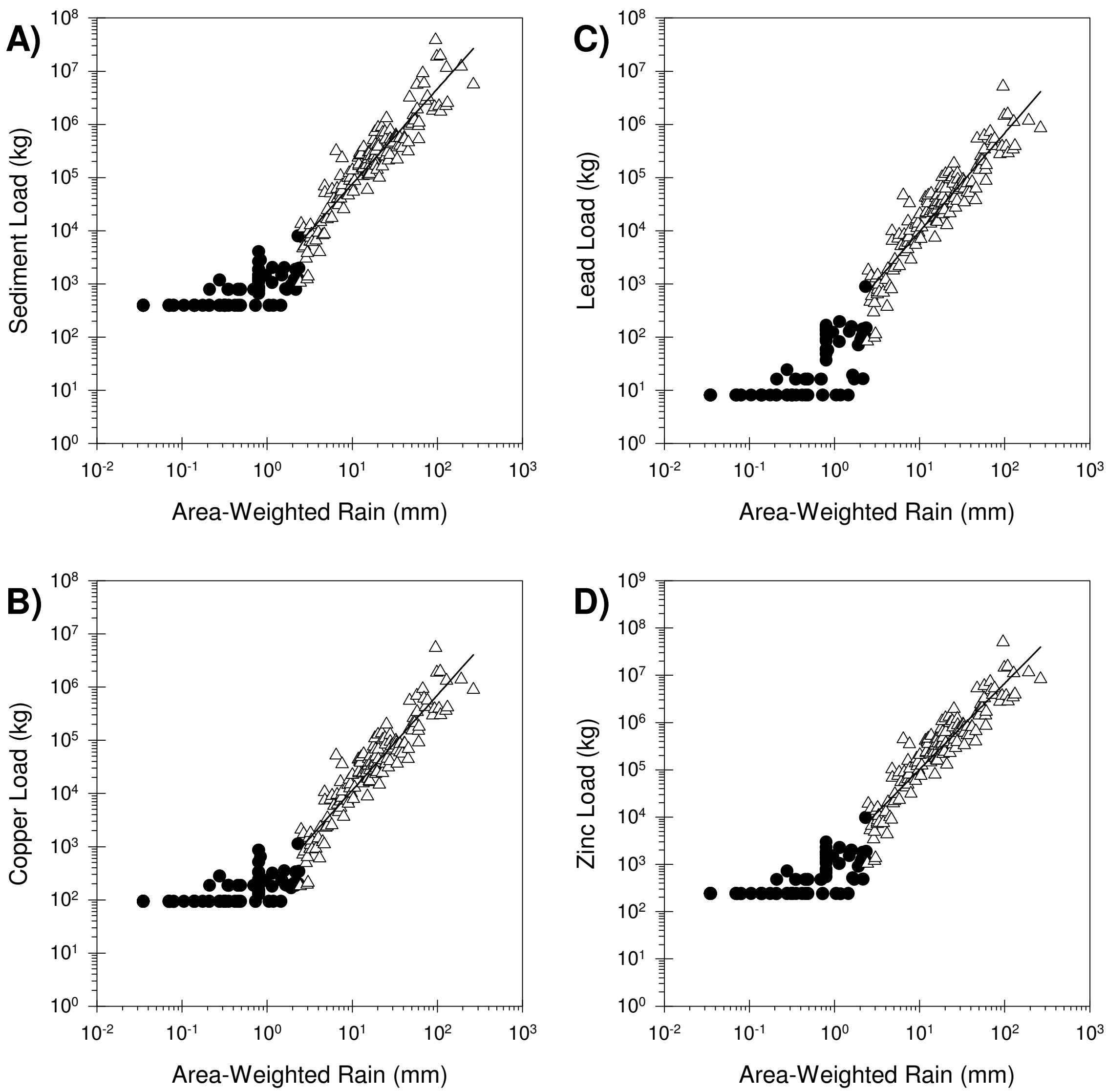

Table 1. Land use area (km^2) and types within each catchment.

	Agriculture	Commercial	High Density Residential	Industrial	Low Density Residential	Mixed Urban	Open	Total Area (km^2)
Percent Pervious	94 %	15 %	40 %	25 %	64 %	50 %	97 %	
Agriculture	0.69	0.02	0.22	0.06				0.98
Commercial 1		1.11	0.04	1.28		0.00	0.02	2.45
Commercial 2		0.06						0.06
High Density Residential 1		0.05	0.44			0.03		0.52
High Density Residential 2			0.01				0.01	0.02
Industrial		0.01		1.99		0.75	0.03	2.77
Low Density Residential 1			0.07		0.89		0.02	0.98
Low Density Residential 2					0.16		0.02	0.18
Open Space 1	0.20				0.30		9.00	9.49
Open Space 2					0.39		2.50	2.90
Ballona Creek - 1		3.86	14.74	4.32	0.09		2.34	25.39
Ballona Creek - 2		2.98	9.62	2.04		0.03	5.23	21.26
Ballona Creek - 3	0.02	12.21	44.80	7.69	0.03	0.27	2.93	68.03
Ballona Creek - 4	0.07	21.17	71.78	3.56	3.39	0.08	16.46	116.99
Ballona Creek - 5		6.61	17.47	3.09	1.04		13.20	41.57
Ballona Creek - 6		3.33	14.93	1.65	1.76	0.03	6.80	29.24
Ballona Creek - 7		2.65	12.43	2.21	5.18	0.01	12.45	35.21

Table 2. Measured storm depth (mm) and antecedent dry days at each land use catchment and Ballona Creek.

Description	2/10/2001		2/19/2001		3/4/2001		4/7/2001		11/24/2001		2/17/2002		3/17/2002		2/24/2003	
	Rain	Days	Rain	Days	Rain	Days	Rain	Days	Rain	Days	Rain	Days	Rain	Days	Rain	Days
Agriculture			6.86	5	27.4	3							1.27	10		
Commercial 1											7.37	20				
Commercial 2			8.13	5			20.3	31								
High Density Residential 1	8.13	16	6.10	5									2.03	27		
High Density Residential 2											8.89	21				
Industrial	8.38	14	6.86	5									2.79	9		
Low Density Residential 1			12.4	5	26.7	3										
Low Density Residential 2													7.87	9		
Open Space 1															6.60	11
Open Space 2															6.60	11
Ballona Creek			6.10	5			11.7	31	15.2	11						

APPENDIX A

Table A1. Model parameters describing suspended sediment washoff and instream behavior.

	Agriculture	Commercial	High Density Residential	Industrial	Low Density Residential	Mixed Urban	Open
Pervious							
Splash detachment							
SMPF	1	1	1	1	1	1	1
KRER	0.35	0.35	0.35	0.35	0.35	0.35	0.35
JRER	2	2	2	2	2	2	2
AFFIX	0.003	0.003	0.003	0.003	0.003	0.003	0.003
COVER	0	0	0	0	0	0	0
NVSI	20	20	20	20	20	20	20
Soil matrix scouring							
KSER	8	8	8	8	8	8	8
JSER	2	2	2	2	2	2	2
KGER	0	0	0	0	0	0	0
JGER	2	2	2	2	2	2	2
Impervious							
KEIM	0.05	0.05	0.1	0.35	0.15	0.05	0.2
JEIM	1	2	2	2	2	2	2
ACCSDP	0.04	0.004	0.004	0.004	0.004	0.004	0.004
REMSDP	0.25	0.025	0.025	0.025	0.025	0.025	0.025

Reach GEN	BEDWID	BEDWRN	POR			
	1	1	0.3			
Reach Sand	D	W	RHO	KSAND	EXPSND	
	0.005	0.02	2.5	0.35	3.2	
Reach Silt	D	W	RHO	TAUCD	TAUCS	M
	0.0006	0.01	2.2	0.15	0.90	3
Reach Clay	D	W	RHO	TAUCD	TAUCS	M
	0.00006	0.0001	2	0.08	0.8	5

SMPF is the supporting management practice factor.
KRER is the coefficient in the soil detachment equation.
JRER is the exponent in the soil detachment equation.
AFFIX is the fraction by which detached sediment storage decreases each day as a result of soil compaction.
COVER is the fraction of land surface that is shielded from rainfall erosion (not considering snow cover, which is handled by the program).
NVSI is the rate at which sediment enters detached storage from the atmosphere.

KSER and JSER are the coefficient and exponent in the detached sediment washoff equation.
KGER and JGER are the coefficient and exponent in the matrix soil scour equation, which simulates gully erosion.

KEIM is the coefficient in the solids washoff equation.
JEIM is the exponent in the solids washoff equation.
ACCSDP is the rate at which solids accumulate on the land surface.
REMSDP is the fraction of solids storage that is removed each day when there is no runoff.

BEDWID is the width of the cross-section over which HSPF will assume bed sediment is deposited.
BEDWRN is the bed depth which, if exceeded (e.g., through deposition) will cause a warning message to be printed in the echo file.
POR is the porosity of the bed (volume voids/total volume).

D is the effective diameter of the transported sand particles, and W is the corresponding fall velocity in still water.
RHO is the density of the sand particles.
KSAND and EXPSND are the coefficient and exponent in the sandload power function formula.
TAUCD is the critical bed shear stress for deposition.
TAUCS is the critical bed shear stress for scour.
M is the erodibility coefficient of the sediment.

Table A2. Model parameters describing copper washoff and instream behavior.

		Agriculture	Commercial	High Density Residential	Industrial	Low Density Residential	Mixed Urban	Open
Pervious								
	POTFW	0.30	1.00	0.80	0.30	0.60	0.80	0.12
	IOQC	4.37e-7	4.37e-7	4.37e-7	4.37e-7	4.37e-7	4.37e-7	4.37e-7
	AOQC	4.37e-7	4.37e-7	4.37e-7	4.37e-7	4.37e-7	4.37e-7	4.37e-7
Impervious								
	POTFW	0.30	1.00	0.80	0.30	0.60	0.80	0.12

Reach GQ-KD	ADPM (1,1)	ADPM (2,1)	ADPM (3,1)	ADPM (4,1)	ADPM (5,1)	ADPM (6,1)
	0.005	0.015	0.015	0.005	0.015	0.015
Reach GQ-ADRATE	ADPM (1,2)	ADPM (2,2)	ADPM (3,2)	ADPM (4,2)	ADPM (5,2)	ADPM (6,2)
	2.5	2.5	2.5	0.2	0.2	0.2
Reach GQ-ADTHETA	ADPM (1,2)	ADPM (2,2)	ADPM (3,2)	ADPM (4,2)	ADPM (5,2)	ADPM (6,2)
	1.07	1.07	1.07	1.07	1.07	1.07

POTFW is the washoff potency factor.
IOQC is the concentration of copper in interflow outflow.
AOQC is the concentration of copper in active groundwater outflow.

ADPM(1,1) through ADPM(6,1) are distribution coefficients with: 1-suspended sand, 2-suspended silt, 3-suspended clay, 4-bed sand, 5-bed silt, and 6-bed clay.

ADPM(1,2) through ADPM(6,2) are transfer rates between adsorbed and desorbed states with: 1-suspended sand, 2-suspended silt, 3-suspended clay, 4-bed sand, 5-bed silt, and 6-bed clay.

ADPM(1,3) through ADPM(6,3) are temperature correction coefficients for adsorption/desorption on: 1-suspended sand, 2-suspended silt, 3-suspended clay, 4-bed sand, 5-bed silt, 6-bed clay.

Table A3. Model parameters describing lead washoff and instream behavior.

	Agriculture	Commercial	High Density Residential	Industrial	Low Density Residential	Mixed Urban	Open
Pervious							
POTFW	0.10	1.00	0.80	0.15	0.20	0.25	0.02
IOQC	4.25e-8	4.25e-8	4.25e-8	4.25e-8	4.25e-8	4.25e-8	4.25e-8
AOQC	4.25e-8	4.25e-8	4.25e-8	4.25e-8	4.25e-8	4.25e-8	4.25e-8
Impervious							
POTFW	0.10	1.00	0.80	0.15	0.20	0.25	0.02

Reach GQ-KD	ADPM (1,1)	ADPM (2,1)	ADPM (3,1)	ADPM (4,1)	ADPM (5,1)	ADPM (6,1)
	0.005	0.015	0.015	0.005	0.015	0.015
Reach GQ-ADRATE	ADPM (1,2)	ADPM (2,2)	ADPM (3,2)	ADPM (4,2)	ADPM (5,2)	ADPM (6,2)
	2.5	2.5	2.5	0.2	0.2	0.2
Reach GQ-ADTHETA	ADPM (1,2)	ADPM (2,2)	ADPM (3,2)	ADPM (4,2)	ADPM (5,2)	ADPM (6,2)
	1.07	1.07	1.07	1.07	1.07	1.07

POTFW is the washoff potency factor.
IOQC is the concentration of lead in interflow outflow.
AOQC is the concentration of lead in active groundwater outflow.

ADPM(1,1) through ADPM(6,1) are distribution coefficients with: 1-suspended sand, 2-suspended silt, 3-suspended clay, 4-bed sand, 5-bed silt, and 6-bed clay.

ADPM(1,2) through ADPM(6,2) are transfer rates between adsorbed and desorbed states with: 1-suspended sand, 2-suspended silt, 3-suspended clay, 4-bed sand, 5-bed silt, and 6-bed clay.

ADPM(1,3) through ADPM(6,3) are temperature correction coefficients for adsorption/desorption on: 1-suspended sand, 2-suspended silt, 3-suspended clay, 4-bed sand, 5-bed silt, 6-bed clay.

Table A4. Model parameters describing zinc washoff and instream behavior.

		Agriculture	Commercial	High Density Residential	Industrial	Low Density Residential	Mixed Urban	Open
Pervious								
	POTFW	2.50	10.20	7.50	4.00	1.20	5.00	0.50
	IOQC	1.13e-6	1.13e-6	1.13e-6	1.13e-6	1.13e-6	1.13e-6	1.13e-6
	AOQC	1.13e-6	1.13e-6	1.13e-6	1.13e-6	1.13e-6	1.13e-6	1.13e-6
Impervious								
	POTFW	2.50	10.20	7.50	4.00	1.20	5.00	0.50

Reach GQ-KD	ADPM (1,1)	ADPM (2,1)	ADPM (3,1)	ADPM (4,1)	ADPM (5,1)	ADPM (6,1)
	0.005	0.015	0.015	0.005	0.015	0.015
Reach GQ-ADRATE	ADPM (1,2)	ADPM (2,2)	ADPM (3,2)	ADPM (4,2)	ADPM (5,2)	ADPM (6,2)
	2.5	2.5	2.5	0.2	0.2	0.2
Reach GQ-ADTHETA	ADPM (1,2)	ADPM (2,2)	ADPM (3,2)	ADPM (4,2)	ADPM (5,2)	ADPM (6,2)
	1.07	1.07	1.07	1.07	1.07	1.07

POTFW is the washoff potency factor.
IOQC is the concentration of the zinc in interflow outflow.
AOQC is the concentration of the zinc in active groundwater outflow.

ADPM(1,1) through ADPM(6,1) are distribution coefficients with: 1-suspended sand, 2-suspended silt, 3-suspended clay, 4-bed sand, 5-bed silt, and 6-bed clay.

ADPM(1,2) through ADPM(6,2) are transfer rates between adsorbed and desorbed states with: 1-suspended sand, 2-suspended silt, 3-suspended clay, 4-bed sand, 5-bed silt, and 6-bed clay.

ADPM(1,3) through ADPM(6,3) are temperature correction coefficients for adsorption/desorption on: 1-suspended sand, 2-suspended silt, 3-suspended clay, 4-bed sand, 5-bed silt, 6-bed clay.